Focus Hope Industries, Inc.
1400 Oakman Blvd., Detroit, MI 48238
CAGE 6KWK9, DUNS 078270052

TITLE: A preliminary report on the strength and metallography of a bimetallic friction stir weld joint between AA6061 and MIL-DTL-46100E High Hardness steel armor.

ABSTRACT

One half inch thick plates of 6061-T6 aluminum alloy and High Hardness steel armor (MIL-STD-46100) were successfully joined by the friction stir welding (FSW) process using a tungsten-rhenium stir tool. Process parameter variation experiments, which included inductive pre-heating, tool design geometry, plunge and traverse rates, tool offset, spindle tilt, and rotation speed, were conducted to develop a parameter set which yielded a defect free joint. Laboratory tensile tests exhibited a maximum yield stress of 176 MPa, which is 91% of the strength of a comparable all-AA6061 FSW joint. Scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDAX) analysis also show atomic diffusion at the material interface region.

COUPON FABRICATION AND TENSILE TESTS

Using an existing FSW coupon fixture mounted to a multi-axes friction stir welder (Transformation Technologies, Inc. GG1 Series), ½-inch thick x 1-inch wide x 8-inches long bars of AA6061-T6 aluminum alloy and high hardness steel (HHS, MIL-STD-46100E High Hardness Wrought Armor) material were subjected to a series of process parameter development experiments. Table 1 lists the specific process parameters that were varied during this study. Figure 1 depicts bimetallic tool offset.

Table 1 – FSW Process Parameters

Parameter	Range
Inductive heating	
Power - pre-heat, plunge/dwell, traverse (kW)	2.5 - 7.5
Time - pre-heat, plunge/dwell, traverse (min)	0.5 - 3.0
Plunge/Dwell	
Plunge tool rotation speed (RPM)	1000
Plunge rate (mm/min)	6 - 30
Dwell tool rotation speed (RPM)	300 - 600
Dwell duration (min)	2 - 3
Traverse	
Tool rotation speed (RPM)	250 - 500
Traverse rate (mm/min)	8 - 50
FSW tool	
Pin diameter (in)	0.3 - 0.5
Pin pitch (degrees)	10.5 - 12
Spindle tilt axis (degrees)	2 - 3
Rotation direction	CW/CCW
Bimetallic offset (mm)	0 - 2.5

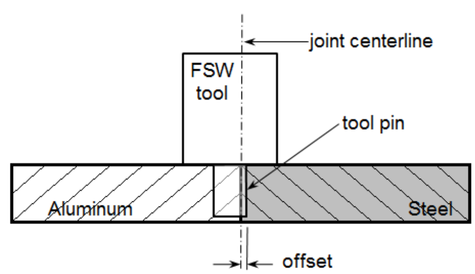

Figure 1 – Bimetallic Tool Offset

To potentially reduce aggressive tool wear observed during another prior FSW study involving the HHS material, an inductive heating system was initially tried as a method to soften the steel material supplemental to the inherent frictional heating of the FSW process. However because of the small bimetallic tool offsets (and therefore minimal tool-to-steel interference) used in this study and adverse effects of the additional heat on the relatively lower solidus

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
26 NOV 2012	**Journal Article**	**15-11-2012 to 15-11-2012**

4. TITLE AND SUBTITLE
A preliminary report on the strength and metallography of a bimetallic friction stir weld joint between AA6061 and MIL-DTL-46100E High Hardness steel armor.

5a. CONTRACT NUMBER
W56HZV-05-C-0721

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Richard Miller

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Focus Hope Industries, Inc.,1400 Oakman Blvd.,,Detroit,Mi,48238

8. PERFORMING ORGANIZATION REPORT NUMBER
; #23476

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army TARDEC, 6501 East Eleven Mile Rd, Warren, Mi, 48397-5000

10. SPONSOR/MONITOR’S ACRONYM(S)
TARDEC

11. SPONSOR/MONITOR’S REPORT NUMBER(S)
#23476

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
One half inch thick plates of 6061-T6 aluminum alloy and High Hardness steel armor (MIL-STD-46100) were successfully joined by the friction stir welding (FSW) process using a tungsten-rhenium stir tool. Process parameter variation experiments, which included inductive pre-heating, tool design geometry, plunge and traverse rates, tool offset, spindle tilt, and rotation speed, were conducted to develop a parameter set which yielded a defect free joint. Laboratory tensile tests exhibited a maximum yield stress of 176 MPa, which is 91% of the strength of a comparable all-AA6061 FSW joint. Scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDAX) analysis also show atomic diffusion at the material interface region.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**Public Release**	**3**	

point aluminum material, the pre-heating system was removed from the parameter matrix but may be required during future experiments.

Initial parameter sets expectedly produced unacceptable weld quality with excessive surface flash and considerable internal defects. After a series of parameter variations, the weld flash was reduced and externally-visible weld voids were eliminated. During a second series of parameter variations, saw-cut joint cross sections were used to determine internal weld quality for each parameter set and further parameters adjustments were made to eliminate weld voids and improve visual weld quality. Finally, a series of welds was made with each weld having a parameter variation of traverse speed or bimetallic tool offset within the process envelop established by the earlier series with all other process parameters common. Several tensile test specimens were extracted from each weld and then tensile tested using an Instron Model 5982 testing machine. Average tests results for each final series parameter set are shown in Table 2.

Table 2 – Tensile Test Results (MPa)

	Yield Strength (MPa)		
Traverse Speed (mm/min)	*Tool Offset (mm)*		
	0.5 mm	*1.0 mm*	*1.5 mm*
10	---	122.00	113.57
20	125.44	138.48	128.25
25	---	148.20	---
30	113.20	120.36	134.96
40	118.84	86.06	129.28
50	---	---	176.02

METALLURGICAL ANALYSIS

A metallurgical analysis specimen was extracted and prepared from a representative joint sample. Figure 2 shows two levels of magnification of a section of the bimetallic joint using a scanning electron microscope (SEM). These images show the intermetallic diffusion of the aluminum material (dark gray) into the HHS (light gray due to etching solution).

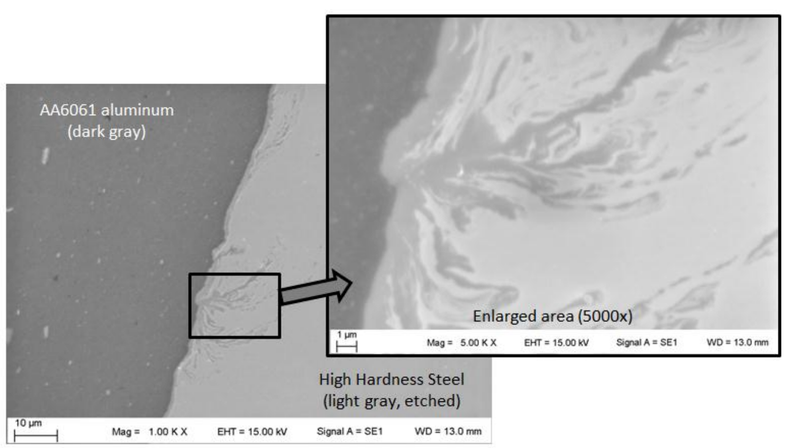

Figure 2 – Scanning Electron Microscope image showing atomic diffusion

CONCLUSIONS

Our analysis indicates metallurgical bonding between the aluminum and steel alloys has occurred with an atomic diffusion zone approximately 2-5 µm wide at the bimetallic interface. Relative to the unwelded constituent materials the transverse tensile strength of the bimetallic FSW joint is significantly weaker, approximately half of the weakest base material AA6061. However relative to the comparative weld joint strengths of single material welds (Table 3), the tensile strength exhibited at this early stage of process development is 58% more than that of an all-AA6061 fusion welded joint and only 9% weaker than an all-AA6061 FSW joint. Additional parameter development and investigations are ongoing and should bring improved results.

Table 3 – Comparing Material and Weld Joint Strength

MATERIAL / WELD TYPE	Yield Strength (MPa)
AA6061-T6511	
base material	345 [a]
GSAW [b]	124 [c]
FSW	194 [d]
High Hardness Steel (HHS)	
base material	1034 [e]
GMAW [f]	tbd [g]
AA6061/HHS FSW joint	176 [8]

[a] Kaiser Aluminum Certified Test Report, Lot #Z00222015
[b] Gas Shielded Arc Weld (GSAW), AA4043 filler
[c] AWS Welding Handbook, Vol. 3, Material and Applications
[d] at FHI April 2011
[e] ATI Allegheny Ludlum 500-MIL™
[f] Gas Metal Arc Weld (GMAW)
[g] under investigation
[h] at FHI Oct 2012

AUTHOR: Richard Miller (richard.miller@focushope.edu)